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## TECHNICAL NOTE

No. 1070

AN EMPIRICAL EQUATION FOR THE COEFFICIENT OF HEAT TRANSFER  
TO A FLAT SURFACE FROM A PLANE HEATED-AIR JET  
DIRECTED TANGENTIALLY TO THE SURFACE

By John Zerbe and James Selna

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SUMMARY

An investigation of the heat transfer to a surface from plane heated-air jets discharged tangentially to the surface was conducted to provide heat-transfer relationships required in the design of heated-air jet installations for aircraft windshield fog prevention.

Experimental temperature, velocity, and heat-transfer data were obtained by tests in which the initial jet temperature and velocity were varied from  $101^{\circ}$  to  $186^{\circ}$  F and from 52 to 218 feet per second, respectively. The jets were produced by three nozzles of different depths: namely, 0.102, 0.318, and 0.547 inch.

The resulting data were correlated to yield relationships for the maximum profile jet velocities and temperatures, and the coefficients of heat transfer from the jet to the surface, in terms of the nozzle-exit jet velocity and temperature and of the distance from the apparent jet origin. The test results are presented in tabular form and the correlations of the data are illustrated graphically.

INTRODUCTION

During an analytical investigation of the use of heated-air jets to prevent fog formations on the inside surface of bullet-resisting windshields, it was found that the required heat-transfer data were not available; consequently, the present investigation on the heat transfer to a surface from

a plane heated-air jet directed tangentially to the surface (hereinafter designated as a surface jet) was undertaken.

The rate of transfer of heat from a surface jet to the surface at a point any distance from the nozzle exit may be defined as equivalent to the product of a coefficient of heat transfer and the difference between the maximum profile temperature in the jet and the temperature of the surface at that point. The coefficient of heat transfer is dependent principally upon the jet velocity and temperature. Equations establishing the relationship between the jet velocity and the major jet parameters of unheated surface jets are available in reference 1 and theoretical temperature relationships for freely expanding heated jets are available in reference 2. The application of this information to heated-surface jets has not been previously accomplished and there are no available expressions for the coefficient of heat transfer for surface jets.

The purpose of the present investigation was to establish relationships generalizing the variation of velocity, temperature, and coefficients of heat transfer in heated-surface jets in order that a rational approach to the use of heated-air jets for fog prevention could be made.

The investigation included the experimental evaluation of the velocity, temperature, and heat-transfer characteristics of heated-surface jets emerging from nozzles of three different configurations at several initial velocity and temperature conditions. The resulting data are correlated in terms of the jet properties at the jet nozzle exit and the relationships developed are generally applicable to the heat transfer from surface jets to smooth flat surfaces when the heat flow to the surface is comparable to that which prevails in a plane heated-air jet installation for aircraft windshield fog prevention.

This investigation was conducted as part of a general study of aircraft windshield fog prevention which was undertaken by the Ames Aeronautical Laboratory at the request of the Bureau of Aeronautics, Navy Department.

#### SYMBOLS

The symbols used in this report are defined as follows:

- c    constant
- d    surface jet-nozzle depth, feet

- $d_r$  reference surface jet-nozzle depth (1/12 ft)
- $e$  distance from apparent jet origin to nozzle exit  
( $d/\tan \alpha$ ), feet
- $h$  coefficient of heat transfer for surface jet, Btu per hour, square foot,  $^{\circ}\text{F}$
- $k_l$  thermal conductivity of Lucite plate, Btu per hour, square foot,  $^{\circ}\text{F}$  per foot
- $k$  thermal conductivity of air, Btu per hour, square foot,  $^{\circ}\text{F}$  per foot
- $L$  distance from nozzle exit to point under consideration, feet
- $l$  thickness of Lucite plate, feet
- $p$  barometric pressure, inches of mercury
- $q$  unit heat transfer through the Lucite plate, Btu per hour, square foot
- $T_m$  maximum profile jet temperature at any distance  $x$ ,  $^{\circ}\text{F}$
- $T_o$  jet temperature at nozzle exit,  $^{\circ}\text{F}$
- $T_a$  ambient-air temperature,  $^{\circ}\text{F}$
- $T_t$  temperature of top surface of Lucite plate,  $^{\circ}\text{F}$
- $T_b$  temperature of bottom surface of Lucite plate,  $^{\circ}\text{F}$
- $\theta_m$  maximum profile jet temperature rise above ambient-air temperature, at any distance  $x$ ,  $^{\circ}\text{F}$
- $\theta_o$  jet temperature at nozzle exit above ambient-air temperature,  $^{\circ}\text{F}$
- $U$  velocity at any point in the jet, feet per second
- $U_m$  maximum profile jet velocity at any distance  $x$ , feet per second
- $U_o$  jet velocity at nozzle exit, feet per second
- $x$  distance from apparent jet origin, feet

$y$	distance perpendicular to surface, feet
$y_r$	distance perpendicular to surface where jet velocity is one-half $U_m$ , feet
$\frac{hx}{k}$	Nusselt number
$\frac{U_{exp}}{\mu}$	Reynolds number
$\rho$	density of air, slugs per cubic foot
$\alpha$	angle of expansion of surface jet, degrees
$\mu$	absolute viscosity of air, pound-seconds per square foot

#### EQUIPMENT AND TEST PROCEDURE

The test equipment employed (fig. 1) consisted of a surface jet nozzle discharging heated air over a Lucite plate (12 in. wide by 24 in. long by 1/4 in. thick), which was mounted above an ice bath. Surface-type thermocouples were installed on the upper and lower surfaces of the Lucite plate (fig. 2) at four stations 5, 10, 15, and 20 inches from the nozzle exit, to measure the temperature drop through the plate. The thermal conductivity of the plate ( $k_l = 0.125$  Btu/hr, sq ft, °F/ft) was determined experimentally and the plate was employed as a heat meter.

Jet velocities and temperatures were measured in a vertical plane extending through the lengthwise center line of the plate. These measurements were made with a velocity-temperature probe (fig. 1) containing a total and a static pressure tube and a thermocouple probe. A micromanometer was employed to determine the jet velocities and the jet temperatures and Lucite-plate surface temperatures were indicated by a Brown, direct-reading, self-balancing potentiometer.

Tests were conducted with three surface jet nozzles (fig. 3) 0.547, 0.313, and 0.102 inch deep at the nozzle exits herein designated as nozzles A, B, and C, respectively. Each nozzle was 12 inches wide. In order to insure uniform jet air flow, the nozzles were all designed to have the exit depth and width prevail for a length of at least 10

nozzle depths before the nozzle exit. Nozzle-exit jet temperatures of approximately 100° and 150° F together with nozzle-exit velocities ranging from 50 to 220 feet per second were employed during the tests. Five to nine tests were conducted with each nozzle, and during each test, measurements of the maximum profile velocity and temperature in the jet and of the heat transferred through the Lucite plate were obtained at each of the four instrumented stations. Velocity profiles were measured at each station during several of the tests conducted with nozzle B.

## RESULTS AND DISCUSSION

The results of the tests are presented in table I. The jet velocities given were calculated from the difference between the total pressure in the jet and the ambient static pressure. The static-pressure measurements in the jet were not used in these calculations because the standard static tube employed erroneously recorded large negative pressures. Other investigators (references 1 and 3) using similar equipment also found this to be true. However, when more refined equipment was employed, they found the correct static pressure in the jet to be approximately one-half percent of the dynamic pressure above ambient static pressure. Therefore, the error involved in using the ambient static pressure is negligible. The rate of heat transfer through the Lucite plate and the coefficients of heat transfer were evaluated by the relationships

$$q = \frac{k_i}{l} (T_t - T_b)$$

and

$$h = \frac{q}{T_m - T_t}$$

A typical set of the velocity profile data obtained during the tests of nozzle B has been plotted nondimensionally,  $U/U_m$  as a function of  $y/y_r$ , in figure 4. The curve drawn on this plot is from a similar plot given in reference 1 for velocity profiles in an unheated surface jet. Since the experimental points conform to the curve, it is evident that the jet temperatures and the heat transfer from the jet had no measurable effect on the velocity

profiles. Thus, it was concluded that relationships defining jet velocities in unheated surface jets could be applied equally well to heated surface jets. Concerning the maximum profile velocities, reference 1 states that the maximum profile velocity  $(U_m)_1$  at any point  $x_1$  is related to the maximum profile velocity  $(U_m)_2$  at any other point  $x_2$  in the same jet by the relationship

$$\frac{(U_m)_1}{(U_m)_2} = \left( \frac{x_1}{x_2} \right)^{-\frac{1}{2}} \quad (1)$$

where  $x$  (fig. 5) is the distance from the apparent jet origin to the point under consideration and may be defined as

$$x = L + e \quad (2)$$

where

$$e = \frac{d}{\tan \alpha} \quad (3)$$

The angle  $\alpha$  is indicated from the data of reference 1 to be approximately  $8\frac{1}{2}^\circ$  and this value is in agreement with that observed during the present tests. Measurements of the maximum profile velocities for each nozzle showed that the initial velocity  $U_0$  was equal to  $U_m$  for a length of approximately  $4d$  from each nozzle exit. Thus, equation (1) may be written as follows:

$$\frac{U_m}{U_0} = \left( \frac{e + 4d}{x} \right)^{\frac{1}{2}} \quad (4)$$

This relationship is compared to the test data in figure 6. The experimental points conform to the curve (equation (4))

to a better degree at the higher values of  $\frac{e + 4d}{x}$ , and it is probable that the relationship is not strictly valid at low values of  $\frac{e + 4d}{x}$ . Low values of  $\frac{e + 4d}{x}$  are encountered at distances  $x$  which are large with respect to the quantity  $e + 4d$ , a constant for any given nozzle depth. The maximum deviation of any of the points from the curve is less than 30 percent.

Theoretical temperature data for freely expanding plane jets (reference 2) show that the maximum profile jet temperatures above ambient-air temperature are proportional to the maximum profile jet velocities. Thus the maximum profile jet temperature data given in table I were plotted nondimensionally ( $\theta_m/\theta_o$ ) as a function of velocity ( $U_m/U_o$ ) in figure 7. The plot provides the relationship

$$\frac{\theta_m}{\theta_o} = \frac{U_m}{U_o} \quad (5)$$

The maximum deviation of any of the test points from equation (5) is less than 25 percent. Equation (5) assumes that the heat transfer to the surface has a negligible effect on the temperature in the jet. This assumption is based on the fact that the heat transferred to the surface is very small in comparison with the heat content of the jet and its validity is amply verified by figure 7. Furthermore, the heat flows obtained during the tests are comparable with those which would prevail in a plane heated-air jet installation for aircraft windshield fog prevention.

The coefficient of heat transfer  $h$  is presumed to be defined from the theory of similarity of heat transfer (reference 4) as

$$\frac{hx}{k} = c \left( \frac{U_o x \rho}{\mu} \right)^n \quad (6)$$

where  $c$  is a constant for any given surface jet. By use of equations (3), (4), and (6) a constant  $c_1$  may be defined for any surface jet as follows: If two surface jets with a common jet origin but of nozzle depths  $d$  and  $d_1$ , respectively, are operated so that at a distance  $x_1$  from the apparent jet origin each has the same maximum profile temperature and maximum profile velocity, the velocity profiles at the point  $x_1$  will be the same for each jet and therefore the coefficients of heat transfer for each jet at that point will be identical. Thus from equation (6)

$$c (U_o)^n = c_1 (U_o)_1^n \quad (7)$$

The combination of equation (7) with equations (3) and (4) yields

$$\frac{c}{d^{n/2}} = \frac{c_1}{d_1^{n/2}}$$

and equation (6) may be written in terms of  $c_1$  and  $d_1$  as

$$\frac{hx}{k} = c_1 \left[ \frac{U_o x \rho}{\mu} \left( \frac{d}{d_1} \right)^{\frac{1}{2}} \right]^n \quad (8)$$

Values of  $hx/k$  and  $\left( \frac{U_o x \rho}{\mu} \right) \left( \frac{d}{d_1} \right)^{\frac{1}{2}}$  have been evaluated in table I using a value of 1/12 foot for  $d_1$ , this value being defined as  $d_r$ . Logarithmic plots of  $hx/k$  as a function of  $\left( \frac{U_o x \rho}{\mu} \right) \left( \frac{d}{d_r} \right)^{\frac{1}{2}}$  for each nozzle tested as well as a comparison of these plots are presented in figure 8. The maximum deviation of any of the test points from the mean curve for any of the plots is less than 20 percent.

The curves of figure 8 all have a slope of 0.65; thus  $n = 0.65$  for all the jet nozzles tested. The plots for nozzles A and B show  $c_1$  to be 0.16, while that for nozzle C yields a value of  $c_1$  of 0.21. It is probable that the value of 0.16 is more reliable, for as pointed out with regard to the velocities, the expressions developed herein may not be strictly valid at low values of  $\frac{e + 4d}{x}$  and all the data for nozzle C were taken at low values of  $\frac{e + 4d}{x}$ . (See fig. 6.) Also, the values of  $d$  may change slightly during actual test operation, and any change in  $d$  would affect the value of  $(d/d_r)^{\frac{1}{2}}$  for nozzle C by a greater amount than it would for the other nozzles. Furthermore, little consideration need be given to the data of nozzle C since nozzles of such a small depth ( $d = 0.102$  in.) would have little practical use. Thus, the equation recommended for the evaluation of the coefficient of heat transfer for surface jets is

$$\frac{hx}{k} = 0.16 \left[ \left( \frac{U_{\infty} \rho}{\mu} \right) \left( \frac{d}{d_r} \right)^{\frac{1}{2}} \right]^{0.65} \quad (9)$$

where  $d_r$  is equal to 1/12 foot.

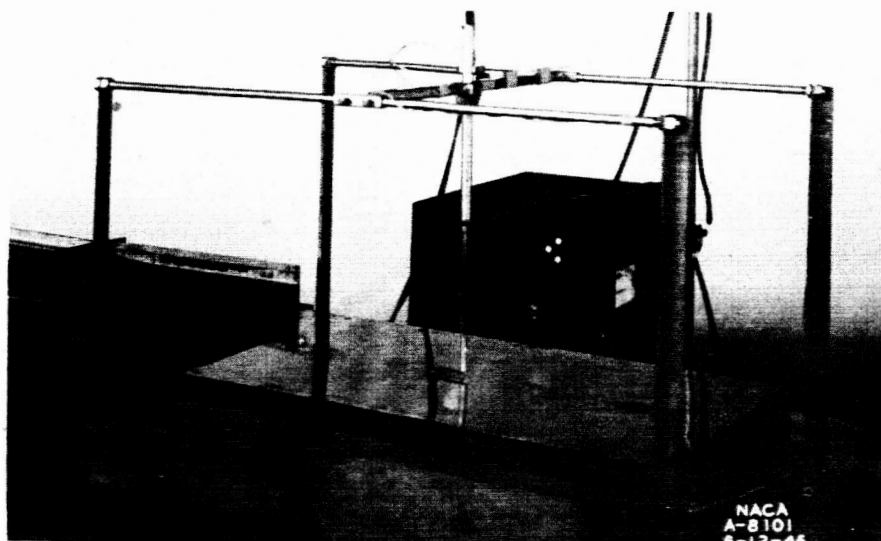
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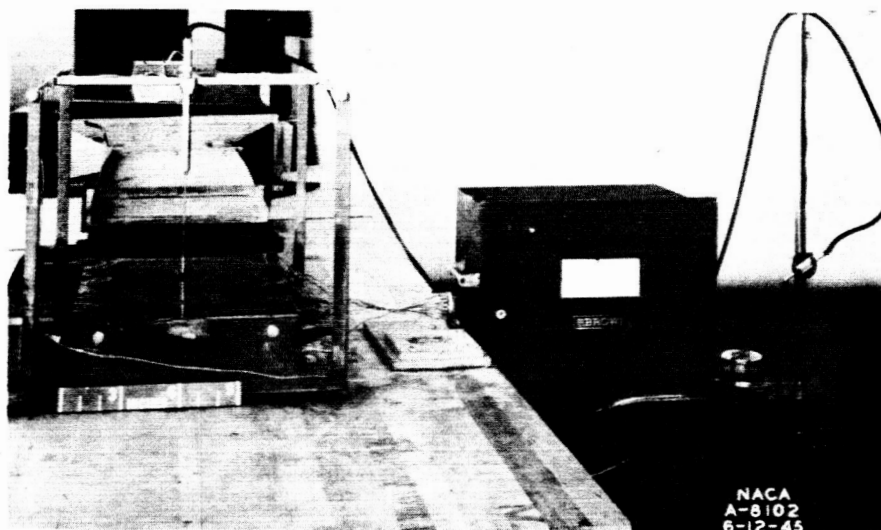
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3. Prandtl, L.: The Mechanics of Viscous Fluids. Vol. III, div. G of Aerodynamic Theory, W. F. Durand, ed., Julius Springer (Berlin), 1935.
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TABLE I.- HEAT-TRANSFER DATA FOR SURFACE JETS DISCHARGED FROM NOZZLES A, B, AND C.

Surface jet nozzle Run number	Nozzle A, d=0.547 in.					Nozzle B, d=0.313 in.										Nozzle C, d=0.102 in.									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			
	29.9	29.9	29.9	29.9	29.9	29.9	30.0	29.9	30.0	29.9	29.8	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0			
Barometric pressure, p (in. Hg)	78	77	77	81	82	78	76	78	77	79	81	81	76	76	79	77	77	79	78	80	82	77			
Ambient air temp., T <sub>a</sub> (°F)	111	101	101	155	190	115	117	109	115	105	146	150	141	140	109	105	105	110	107	156	145	147			
Jet temp. at nozzle exit, T <sub>0</sub> (°F)	52	107	156	56	112	54	72	108	126	154	56	76	104	190	113	120	148	163	210	119	169	218			
Jet velocity at nozzle exit, U <sub>0</sub> (ft/sec)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			
Maximum jet temp., T <sub>m</sub> (°F)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			
Maximum jet velocity, U <sub>m</sub> (ft/sec)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			
Lucite plate top surface temp., T <sub>t</sub> (°F)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			
Lucite plate bottom surface temp., T <sub>b</sub> (°F)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			
Heat transferred through lucite plate, q (Btu/hr, ft <sup>2</sup> )	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			
Coefficient of heat transfer from jet to plate, h (Btu/hr, ft <sup>2</sup> , °F)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			
Nusselts number $\frac{h x}{k}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			
Reynolds number $\frac{U_0 x \rho}{\mu} \times 10^{-4}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			
$\frac{U_0 x \rho}{\mu} \left( \frac{d_1}{d_2} \right)^{\frac{1}{2}} \times 10^{-4}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			



(a) Side view



(b) Front view

Figure 1.- Side and front views of surface jet test apparatus.

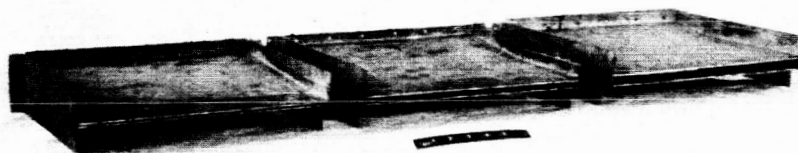


Figure 3.- Surface jet nozzles A, B, and C.  
(Right to left.)

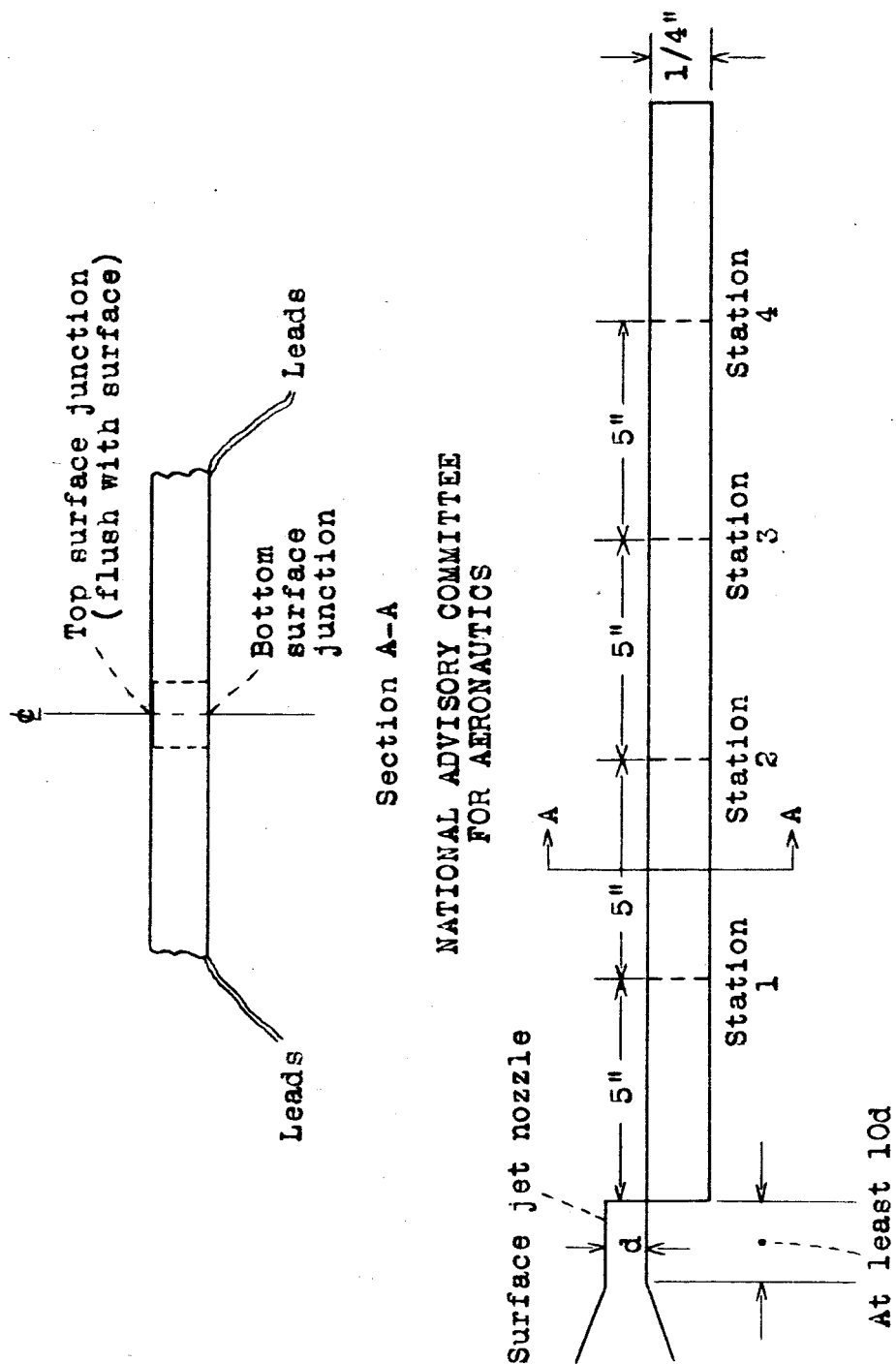


Figure 2.- Location of surface thermocouples on Lucite plate.

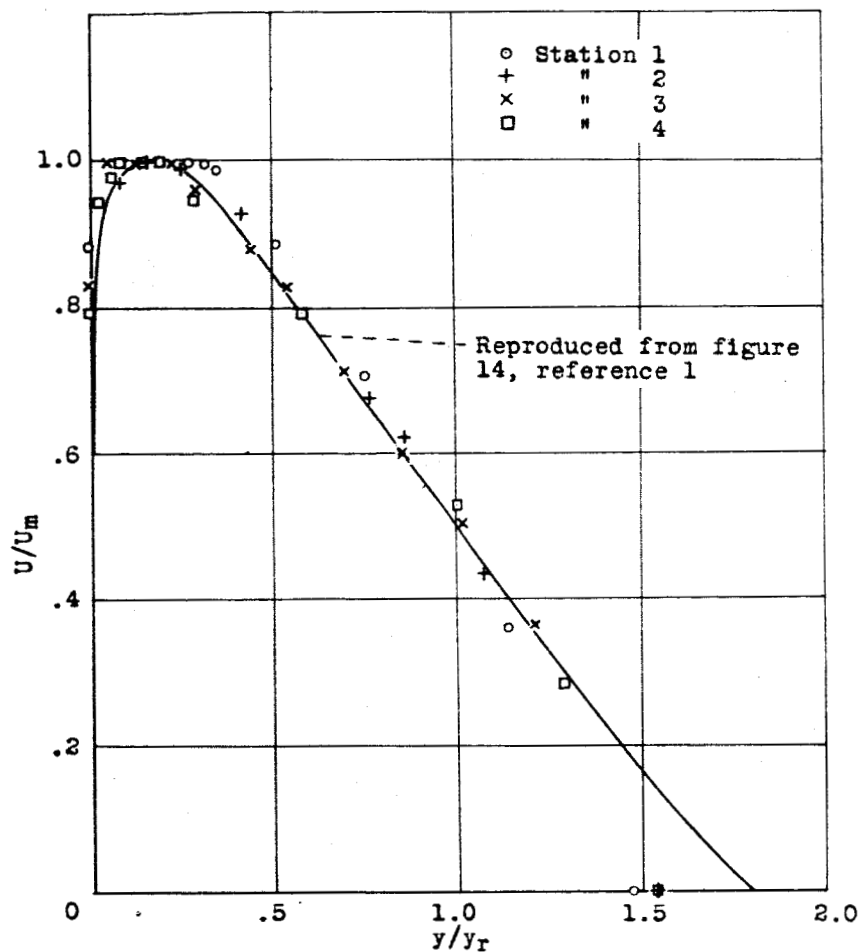


Figure 4.- Typical set of velocity profile data compared with nondimensional velocity profile curve of reference 1.

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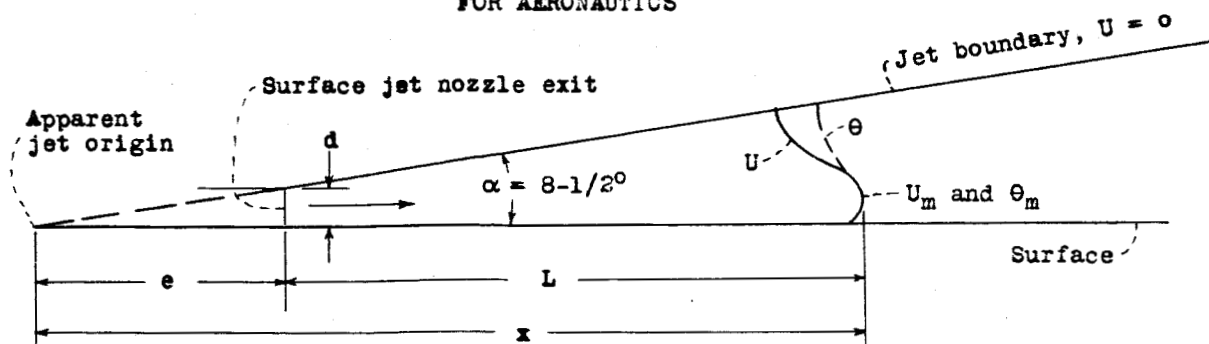


Figure 5.- Surface jet configuration.

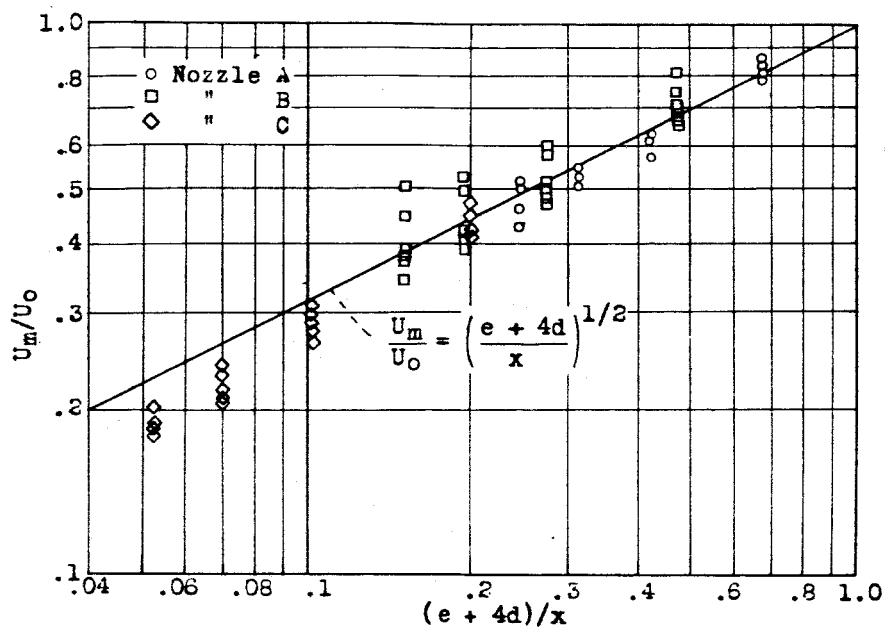


Figure 6.- Velocity ratio  $U_m/U_0$  as a function of distance ratio  $(e + 4d)/x$ .

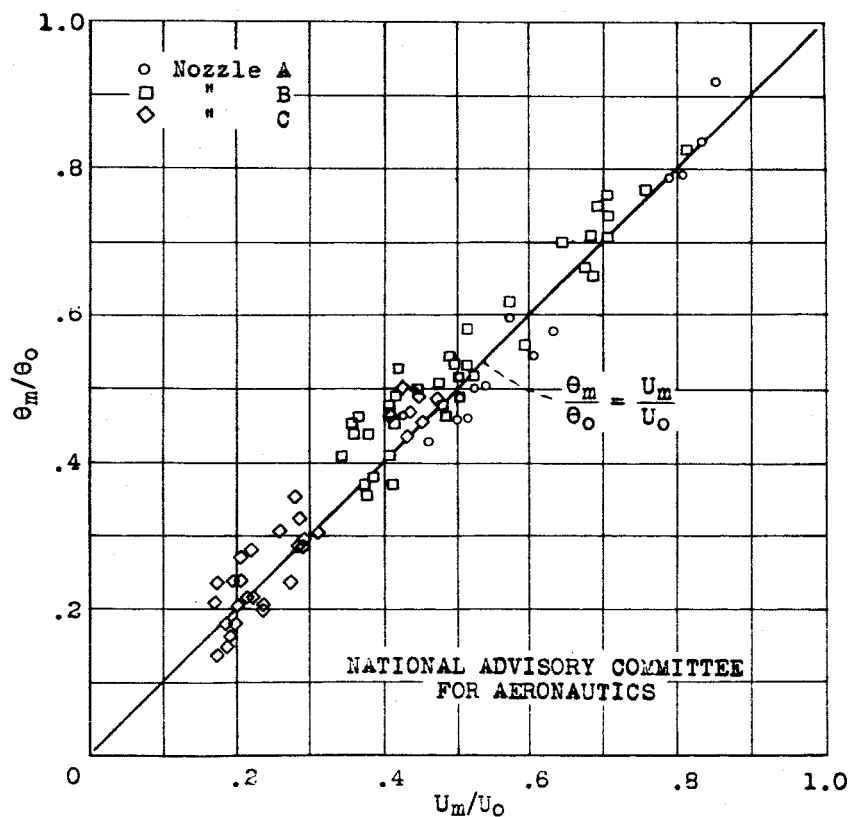
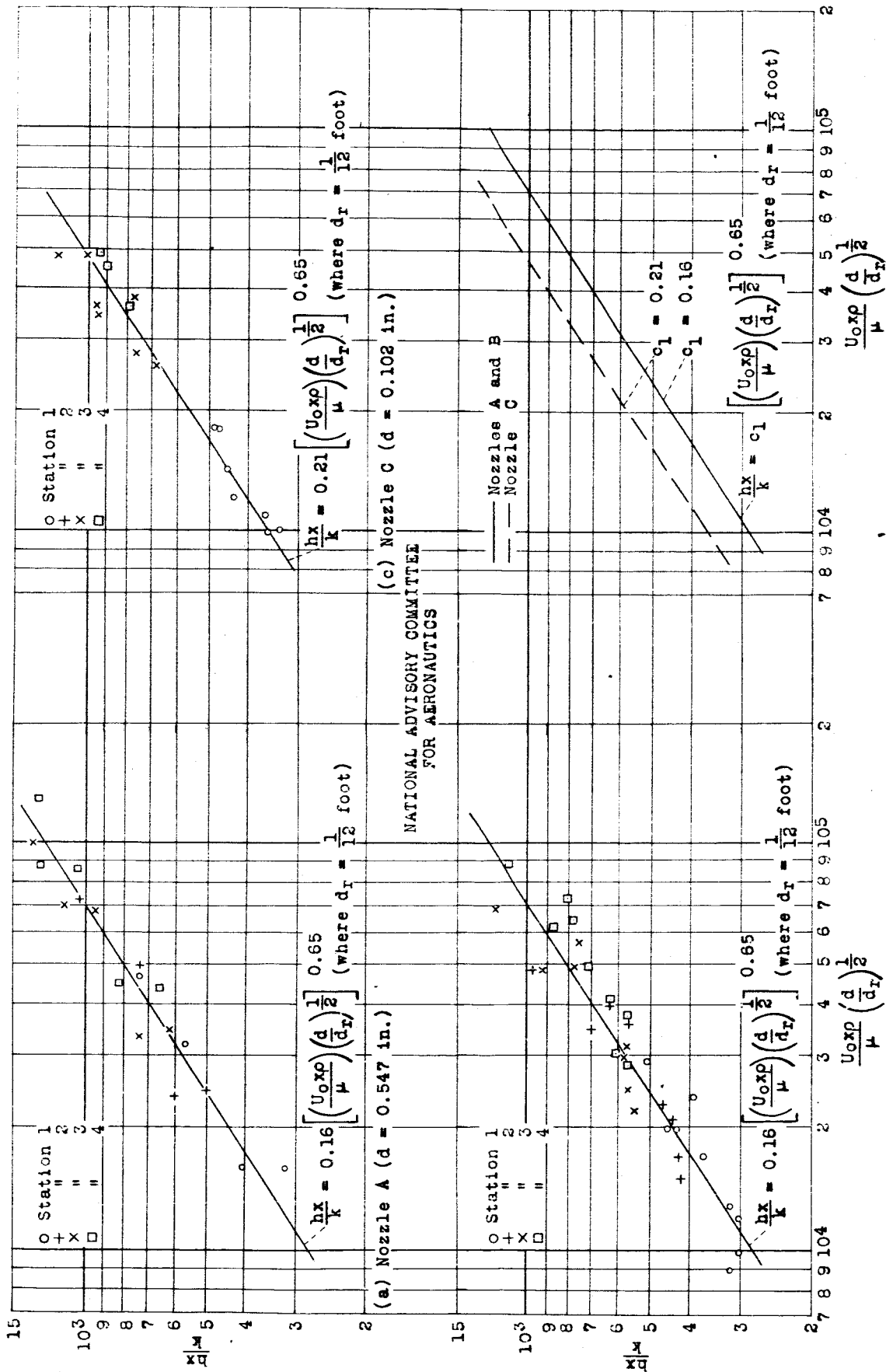


Figure 7.- Temperature ratio  $\theta_m/\theta_0$  as a function of velocity ratio  $U_m/U_0$ .

(b) Nozzle B ( $d = 0.313$  in.)

(d) Comparison of data for Nozzles A, B, and C.

Figure 8.- Nusselts number as a function of  $\frac{U_{0 \exp}}{\mu} \left( \frac{d}{d_r} \right)^{\frac{1}{2}}$  for surface jets tested.